On the oxygen isotopic composition of the Solar System

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ABSTRACT

The $^{18}O/^{17}O$ ratio of the Solar System is 5.2 while that of the interstellar medium (ISM) and young stellar objects is $\sim$4. This difference cannot be explained by pollution of the Sun's natal molecular cloud by ^{18}O-rich supernova ejecta because (1) the necessary B-star progenitors live longer than the duration of star formation in molecular clouds; (2) the delivery of ejecta gas is too inefficient and the amount of dust in supernova ejecta is too small compared to the required pollution (2% of total mass or $\sim$20% of oxygen); and (3) the predicted amounts of concomitant short-lived radionuclides (SLRs) conflicts with the abundances of ^{26}Al and ^{41}Ca in the early Solar System. Proposals for the introduction of ^{18}O-rich material must also be consistent with any explanation for the origin of the observed slope-one relationship between $^{17}O/^{16}O$ and $^{18}O/^{16}O$ in the high-temperature components of primitive meteorites. The difference in $^{18}O/^{17}O$ ratios can be explained by enrichment of the ISM by the ^{17}O-rich winds of asymptotic giant branch (AGB) stars, the sequestration of comparatively ^{18}O-rich gas from star-forming regions into long-lived, low-mass stars, and a monotonic decrease in the $^{18}O/^{17}O$ ratio of interstellar gas. At plausible rates of star formation and gas infall, Galactic chemical evolution does *not* follow a slope-one line in an three-isotope plot, but instead moves along a steeper trajectory towards an ^{17}O-rich state. Evolution of the ISM and star-forming gas by AGB winds also explains the difference in the carbon isotope ratios of the Solar System and ISM.

Subject headings: astrochemistry — solar system: formation — ISM: evolution — Galaxy: evolution — stars: AGB and post-AGB

1. Was the protosolar cloud polluted by a supernova?

Abundance ratios of the three stable isotopes of oxygen (^{16}O,^{17}O,^{18}O) in meteorites and planetary samples are used to infer the existence of reservoirs and processes in the early Solar System. Each of these isotopes was produced in a different mass-distribution of stars, and the isotopic composition of the Solar System is the cumulative result of $\sim$9 billion years (Gyr) of previous Galactic stellar nucleosynthesis. ^{16}O, a primary isotope, is principally formed during He-burning in massive stars, and added to the ISM by core-collapse supernovae (Type II SNe). ^{17}O and ^{18}O are secondary isotopes: The first is produced by reaction of light nuclei during the CNO cycle; the second by nitrogen reactions during He burning. Both of the heavier isotopes are ejected by Type II SNe. ^{17}O is also produced by the intermediate-mass progenitors of asymptotic giant branch (AGB) stars. The yield scales with the abundance of ^{16}O (Meyer et al. 2008). Thus, in a plot of ^{17}O/^{16}O vs. ^{18}O/^{16}O, Galactic chemical evolution (GCE) is expected to proceed along a slope-one line (Timmes et al. 1995). Comparisons of the Sun with gas and other objects in the Milky Way should reveal such a trend, with younger objects being relatively ^{16}O poor.

Observations to date do not fulfil this expectation. Measurements of primordial Solar System materials, including the solar wind returned by *Genesis* spacecraft (McKeegan et al. 2009), fall along a slope-one line that has a high ^{18}O/^{17}O (but not high ^{16}O) compared to the much younger ISM and newly-formed stars (Wannier 1980; Wilson & Root 1994; Wouterloot et al. 2008). One proposed explanation is that the Solar System formed from molecular gas polluted by ^{18}O-rich gas from massive stars (Olive & Schramm 1982; Henkel & Mauersberger 1993; Young et al. 2009). SLRs such as ^{26}Al, ^{41}Ca and ^{60}Fe in the early Solar System are interpreted as evidence that contamination did occur (Goswami et al. 2005). However, the oxygen isotopic composition of the Solar System falls along the same trend inferred for the initial compositions of AGB stars that

formed before the Sun and produced the presolar oxide grains in primitive meteorites (Nittler 2009). Furthermore, to explain the oxygen isotopic composition of the Solar System, (1) the delivery of SN ejecta must have occurred before cessation of star formation in the cloud, (2) it must have been efficient enough to produce the observed offset, (3) it must be quantitatively consistent with the abundance of SLRs, and (4) it must be compatible with the observed slope-one dispersion of primitive Solar System materials and the solar wind in a three-isotope plot (δ^{17}O vs. δ^{18}O), if this dispersion is primary (see below). We argue that the SN pollution hypothesis fails all four tests.

First, stellar nucleosynthesis calculations show that *only* B-star progenitors (8-15 M$_\odot$) have SN ejecta with ^{18}O/^{17}O ratios substantially higher than the current ISM (Meyer et al. 2008) and are plausible sources of pollution. However, these stars have main-sequence lifetimes >15 Myr, longer than the typical duration of star formation in clouds (Williams et al. 2000; Lada & Lada 2003), and thus low-mass stars forming from the same cloud are unlikely to be polluted. The probability of an unaffiliated B star polluting a given cloud during its lifetime is approximately $R\tau f$, where $R \sim 2 \times 10^4$ Myr^{-1} is the Type II SN rate in the Milky Way (Dragicevich et al. 1999) (mostly from B star progenitors), $\tau \sim 10$ Myr is the mean cloud lifetime (Lada & Lada 2003), and $f \sim 10^{-8}$ is the volume filling factor of a 10 pc cloud in the Galactic disk. The probability is $\sim$0.2%, comparable to that of an encounter with an AGB star (Kastner & Myers 1994).

Second, mixing between hot, tenuous SN ejecta and cooler, denser molecular gas is inefficient. A 3-dimensional simulation produced mixing of 50 ppm (Boss et al. 2008), only 2.5% of what is required. Refractory grains of Al$_2$O$_3$ can carry ^{26}Al into a cloud (Gaidos et al. 2009), but can accommodate only 0.9% of all oxygen (Lodders 2003). SN are predicted to be copious sources of dust, but no more than 10^{-5}-10^{-4} M$_\odot$ has been detected per event (Meikle et al. 2007). The scarcity of ^{16}O-rich presolar grains of plausible SN

origin (Hoppe & Zinner 2000) also supports inefficient SN dust production and transfer to star-forming regions.

Third, SLRs such as ^{26}Al, ^{41}Ca, and ^{60}Fe, with half-lifes of 0.72, 0.1 Myr, and 2.6 Myr (Rugel et al. 2009), respectively, accompanied SN ejecta and Wolf-Rayet winds from massive stars, and SLR abundances and any oxygen isotopic shift should be related (Gounelle & Meibom 2007). Previous work has shown that introduction of exogenous SLRs would likely have occurred during the giant molecular cloud phase (Gaidos et al. 2009). ^{26}Al was homogeneously distributed in the protosolar nebula with the ratio ^{26}Al/^{27}Al $\approx 5 \times 10^{-5}$ (Thrane et al. 2006; Villeneuve et al. 2009). The allowed fraction of SN ejecta depends on the interval of free decay of ^{26}Al between injection and the formation of refractory calcium-aluminum-rich inclusions (CAIs, taken to represent time zero). The abundance of ^{41}Ca constrains the interval of free decay to $\sim$0.3 Myr, and Monte Carlo calculations show that the Solar System most likely formed from a cloud polluted to 0.3% by a generation of stars that formed 4.5 Myr earlier (Gaidos et al. 2009). Only progenitors more massive than 50 M$_\odot$ could pollute, but such stars are depleted in both ^{17}O and ^{18}O with respect to the Solar System. Limongi & Chieffi (2003) predict that the ejecta from a 35 M$_\odot$ progenitor contains 5, 1.7×10^{-5}, and 5×10^{-5} M$_\odot$ of ^{16}O, ^{17}O, and ^{18}O, respectively. [See Woosley & Weaver (1995) for similar figures.] This ^{16}O-rich material leaves the ^{18}O/^{17}O ratio of the cloud essentially unchanged. Ejecta from higher-mass progenitors is expected to be even more depleted in ^{17}O and ^{18}O.

The high-temperature components (chondrules and CAIs) of unaltered chondritic meteorites plot along a slope-one line in a three-isotope oxygen diagram (Yurimoto et al. 2007)[1].

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[1]Only rare FUN (Fractionation and Unidentified Nuclear effects) and F (Fractionation) CAIs show evidence for extensive mass-dependent isotope fractionation due to melt evaporation and plot along lines with slope of 0.52 (Krot et al. 2009)

The dispersion is usually explained by models in which (1) the initial oxygen isotopic compositions of both solids and gas were identical and equal to the solar wind value returned by *Genesis*; and (2) the slope-one line is a consequence of mixing with an ^{16}O-poor reservoir generated in the protoplanetary disk by "self-shielding" of CO isotopomers from ultraviolet dissociation, e.g. Lyons & Young (2005). However, these assumptions have been challenged by Krot et al. (2009), who concluded that (1) primordial (thermally unprocessed) solids in the Solar System were already ^{16}O-depleted relative to solar nebula gas; and (2) CO self-shielding had only a small effect on the isotopic chemistry of dust in the Solar System. In this scenario, the slope-one line was produced by mixing of *relict*, isotopically distinct reservoirs, i.e. gas and dust of different ages (Dwek 2006). Any contamination by ^{18}O-rich ejecta would have to be contrived such that the final slope-one line was preserved.

2. The Solar System in the context of Galactic chemical evolution

The isotopic composition of the Solar System can be explained in terms of GCE that has deviated from the canonical slope-one line at least since the Sun formed 4.6 Gyr ago. A flat age-metallicity relation (Holmberg et al. 2007) and the deficit of metal-poor stars in the solar neighborhood (Caimmi 2008) indicate that the metallicity of star-forming gas has evolved little over the past $\sim$10 Gyr, presumably because of the infall of metal-poor gas and the sequestration of metals in low-mass stars (Colavitti et al. 2008). This means that the recent evolution of the ^{17}O/^{16}O and ^{18}O/^{16}O ratios in the Milky Way depended not on ^{16}O, but on the relative contributions by stars of different masses to each isotope, and the time-variation caused by the strong dependence of main sequence lifetime on stellar mass.

The ISM is neither a closed system nor chemically and isotopically homogeneous. Gas and dust move through different phases (molecular clouds, neutral ISM, HII regions), and stars with different masses add or remove isotopes at different times depending on their

main sequence life. A GCE model should include: (1) infall of metal-poor, ^{16}O-rich gas; (2) massive progenitors of SN (and Wolf-Rayet stars) which begin ejecting mass 1-3 Myr after the formation of their progenitors (Limongi & Chieffi 2003) and can pollute their natal molecular cloud (Gaidos et al. 2009); (3) stars with initial masses of 1.5-8 $M_\odot$ which move onto the red giant and asymptotic branches >70 Myr after their formation, long after dispersal of the molecular cloud, eject mass into low-density ISM phases, and preferentially enrich them in ^{17}O with respect to star-forming regions[2]; and (4) stars with <1 $M_\odot$ which remain on the main sequence for >12 Gyr and are a sink for all isotopes. The sequestration of relatively ^{18}O-rich gas from star-forming regions will leave the ISM enriched in ^{17}O. We propose that the cumulative effect is GCE with a stagnant ^{18}O/^{16}O ratio but a decreasing ^{18}O/^{17}O ratio, and that the difference between the Sun (and all stars of its age) and gas in the present Milky Way is a result of this gradual change.

We calculated the evolution of the oxygen isotopic composition in the vicinity of the Sun's formation and present location using a two-box model of GCE. One box represents the low-density phases of the ISM (hereafter referred to as the ISM), which receives metal-poor infalling gas, gas ejected from star-forming regions, winds from AGB stars, and some SN ejecta. The second box represents star-forming regions (molecular clouds). It receives gas from the ISM, returning (most of) it after disruption of the clouds, and the difference is incorporated into stars. Three types of stars are considered: low-mass stars (< 1 $M_\odot$) which only sequester mass; intermediate-mass progenitors of AGB stars, and high-mass (> 8 $M_\odot$) SN progenitors. SNe eject mass into either molecular clouds or the ISM, depending on their main-sequence life relative to the cloud lifetime (10 Myr); AGB stars pollute only the ISM. The mass flux from the ISM into molecular clouds is calculated using a fixed

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[2]One manifestation of this is the appearance of ^{17}O-rich presolar grains in primitive meteorites (Nittler et al. 1997; Nittler 2009).

ISM residence time of 280 Myr, a value calculated from a total gas surface density of 14 $M_\odot$ pc^{-2} in the present solar neighborhood (Naab & Ostriker 2006), a star formation efficiency of 10% (Williams et al. 2000; Lada & Lada 2003), and a local star-formation rate of 5×10^{-3} $M_\odot$ pc^{-2} Myr^{-1}. This last value is based on a SN rate of 0.04 yr^{-1} (Dragicevich et al. 1999) and the abundance of ^{26}Al in the Milky Way (Diehl et al. 2006). This residence time is consistent with previous estimates (Tenorio-Tagle 2000) and the interstellar residence times of presolar grains (Heck et al. 2009). The return flow of gas through HII regions and the disruption of molecular clouds by SN assumes a cloud residence time of 10 Myr (Williams et al. 2000; Lada & Lada 2003). We relate star-formation rate to total gas density by a Schmidt-Kennicut law with an index of 1.45 (Fuchs et al. 2009). We adopt a power-law stellar initial mass function with index of 2.35 for > 1 $M_\odot$ and take the fraction of stellar mass in lower-mass stars to be 0.42.

The present gas infall rate is poorly constrained by direct observations, but rates have been inferred from the distribution of stellar metallicities. We assume a constant rate based on a recent analysis of G- and K-star metallicities (Casuso & Beckman 2004). Moreover, the adopted relationship between star-formation and gas surface density, and the current *total* mass density in the solar neighborhood [$\sim$50 $M_\odot$ pc^{-2} (Naab & Ostriker 2006)] restrict the range of possible infall rates in our model. A rate of 3.5×10^{-3} $M_\odot$ pc^{-2} Myr^{-1} successfully reproduces the present surface densities of gas, stars, and stellar remnants [14, 35, and 3 $M_\odot$ pc^{-2}, respectively (Naab & Ostriker 2006)]. The infalling gas is assumed to contain 10% solar ^{16}O and no ^{17}O or ^{18}O.

Nucleosynthetic yields are taken from Woosley & Weaver (1995) for SN and from Boothroyd & Sackmann (1999) for AGB stars. We do not consider stars more massive than 40 $M_\odot$, for which detailed yields have yet to be published. These stars are thought to contribute negligible ^{17}O or ^{18}O. Dependence on metallicity is determined by linear

interpolations between solar and single sub-solar values. The ^{17}O yield from massive stars might have to be adjusted significantly downwards because of revised values for the proton capture reaction rates ^{17}O(p,α)^{14}N and ^{17}O(p,α)^{18}F (Meyer et al. 2008). Removing the contribution from massive stars to ^{17}O altogether results in a model ^{17}O/^{16}O ratio in star-forming regions 4.6 Gyr ago that is within 15% of the solar value. With unadjusted ^{18}O yields, the model predicts an ^{18}O/^{16}O ratio that is within 7% of the solar value. We are unable to simultaneously reproduce the surface densities of stars and gas, *and* the absolute oxygen abundance of star-forming clouds 4.6 Gyr ago (i.e. the solar abundance). One solution, besides tuning yields, is start the assembly of the disk at the Sun's location only 10 Gyr ago, i.e. 3.5 Gyr after the formation of the Galactic center (Naab & Ostriker 2006). Another is to allow a small fraction of the oxygen-enriched gas from star-forming regions to permanently escape the disk and be replaced with metal-poor gas.

Figure 1 shows the predicted evolution of the oxygen isotope ratios in both the ISM (diamonds) and star-forming regions (squares) with respect to values in star-forming regions 4.6 Gyr ago (taken to represent the solar value). GCE is towards a ^{16}O-poor, but relatively ^{17}O-rich condition: it does *not* follow a slope-one line. In our model, the difference in ^{18}O/^{17}O between the ISM and star-forming regions is due only in small part to contamination of clouds by SN, because only progenitors of 18-40 M$_\odot$ are sufficiently short-lived and these contribute little ^{18}O. Instead, it is mostly due to contamination of the ISM with ^{17}O from AGB stars over the ~280 Myr it takes for the two reservoirs to exchange.

Episodic gas infall or star formation produces yet more dramatic departures from a slope-one trajectory. Cosmological models predict stochastic time variation associated with infalling dark matter halos (Colavitti et al. 2008), and accompanied by elevated rates of star formation. If the Sun formed during a ~1 Gyr episode of increased star formation

(twice the background rate), it partakes of an enhanced ^{18}O-rich contribution from massive stars (Figure 2) before winds from AGB stars return the ISM to its previous isotopic trajectory. In a sense, this *is* SN pollution, but on a Galactic scale.

3. Discussion

Our model of GCE in the solar neighborhood produces a super-unity slope in a three-oxygen isotope plot, and can explain the high ^{18}O/^{17}O ratio of the Sun with respect to the ISM. The absence of this phenomenon in previous models (Prantzos et al. 1996) may be attributable to the assumption that stars form from a gas of mean disk composition, rather than one to which AGB stars of the same generation have yet to contribute. Our model also predicts a difference between the composition of the ISM and star-forming regions: such a difference has not been observed (Young et al. 2009) but *measurements of oxygen isotopes are currently possible only in molecular (i.e. CO-containing) gas* and the composition of the low-density phases of the ISM is unknown. The composition of young stellar objects also appears to be dispersed along a slope-one line in a three oxygen isotope plot. This effect could be produced by heterogeneous mixing of Galactic disk gas with infalling, metal-poor gas lacking ^{17}O and ^{18}O (Figures 1 and 2).

A purported Galactocentric gradient in oxygen isotopes (increasing ^{16}O with radius) (Wilson & Root 1994) is cited as support for standard GCE: However, recent data do not exhibit a significant trend (Polehampton et al. 2005), and while the ^{18}O/^{16}O ratio at the Galactic center may be higher than disk values, the former may have been previously overestimated (Wouterloot et al. 2008). Instead, Wouterlout et al. (2008) report an increasing ^{18}O/^{17}O ratio with Galactocentric radius and a lower ^{18}O/^{17}O in the Large Magellanic Cloud (LMC) compared to similarly metal-poor regions of the outer disk. They explain both of these observations as a result of the accumulation of ^{17}O with time, i.e.

both the inner disk and LMC are older than the outer disk. A corollary of this conclusion is that at any given Galactocentric radius, younger objects (e.g., the ISM and newly-formed stars) will be more ^{17}O-rich than older ones (e.g., the Solar System).

Our scenario predicts that most low mass stars of the Sun's age should have a similar oxygen isotopic composition. The SN contamination scenario, in contrast predicts that the Sun lies at the extreme of a distribution of ^{18}O/^{17}O ratios (corresponding to different levels of contamination), something the observations so far do not suggest. While it is presently not possible to measure the oxygen isotopic composition of main-sequence stars, other isotopes such as those of Mg (Yong et al. 2004) or Si (Tsuji et al. 1994) might serve as proxies.

The ^{12}C/^{13}C ratio of the Solar System (89±1) (Wyckoff et al. 2000; Clayton & Nittler 2004) is higher than the interstellar ratio in the solar neighborhood (76 ± 7) (Stahl et al. 2008). This difference can be explained by the high ^{13}C/^{12}C ratio in winds from red giant branch and AGB stars (Timmes et al. 1995; Milam et al. 2005), although chemical inhomogeneities in the ISM may also be important (Stahl et al. 2008). The present-day C and O isotopic composition of the ISM at the Galactocentric location of the Sun's birth is consistent with mixing of average AGB winds with the ISM 4.6 Gyr ago (represented by the Solar System) (Figure 3).

Our arguments do not preclude *any* pollution of the Sun's parent molecular cloud by massive stars, but demonstrate that the required amount and kind of pollution is neither plausible nor necessary to explain the ^{18}O/^{17}O ratio of the Solar System. The Solar System's initial inventory of ^{26}Al from the ejecta of $M > 50 M_\odot$ stars would have been accompanied by a shift of about -65‰ in both heavy isotopes. If this ^{17}O- and ^{18}O-depleted oxygen was delivered primarily as gas to the natal molecular cloud, it would have established an offset between the isotopic compositions of gas and dust in the cloud along the slope-one line.

This, as well as mixing with infalling metal-poor gas, could explain the slope-one dispersion in primitive meteorite components and the solar wind (Krot et al. 2009).

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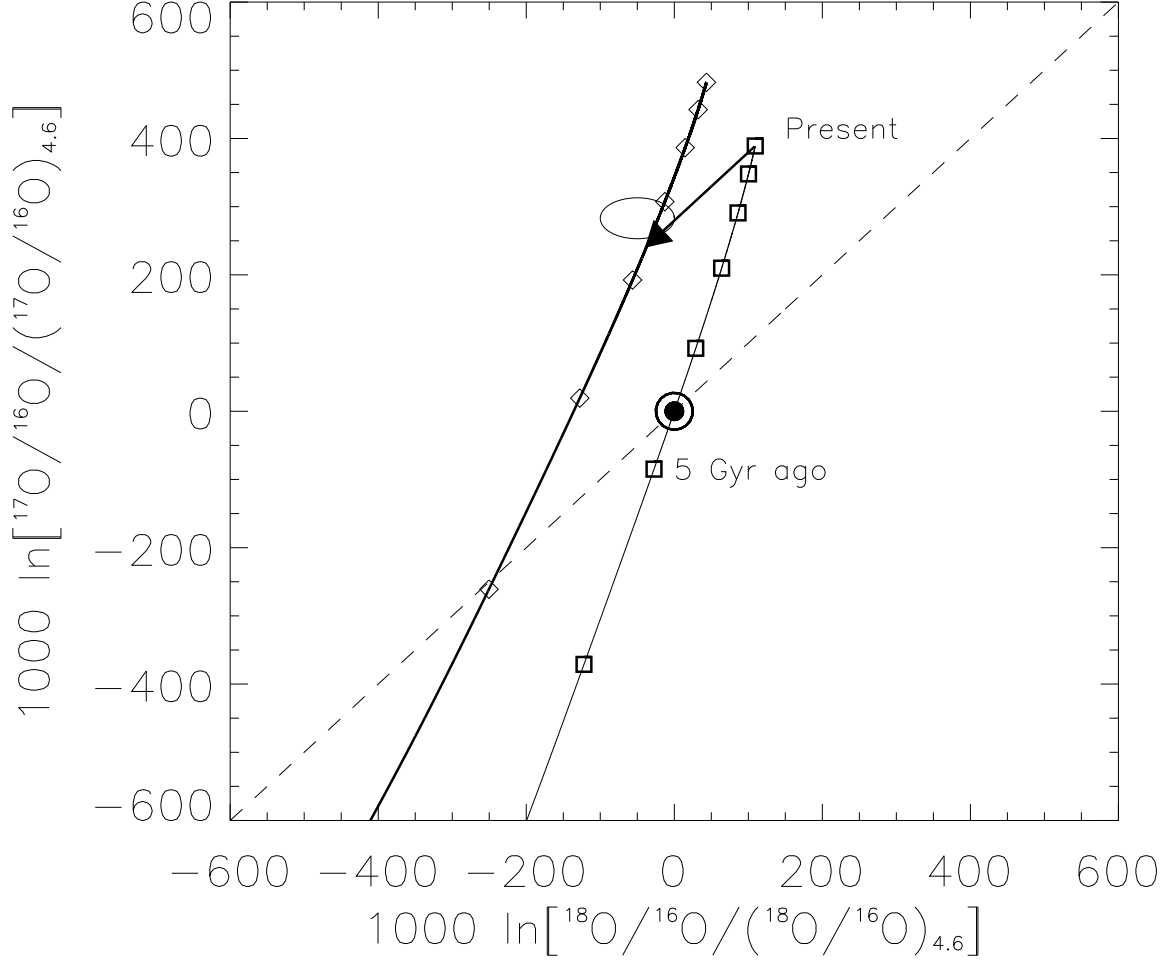
Fig. 1.— Predicted evolution over 10 Gyr of the three oxygen isotope in the ISM (diamonds) and star-forming regions (squares) at 1 Gyr intervals, terminating in the upper right at the present day. Units are 1000× the natural log of ratios with the value 4.6 Gyr ago when the Sun formed. The open ellipse is the composition of the ISM relative to the Solar System (Wouterloot et al. 2008). The dashed line is the standard slope-one GCE trajectory. The arrow is the mixing line produced by adding 20% gas with 10% solar ^{16}O and zero ^{17}O and ^{18}O to present-day star-forming regions.
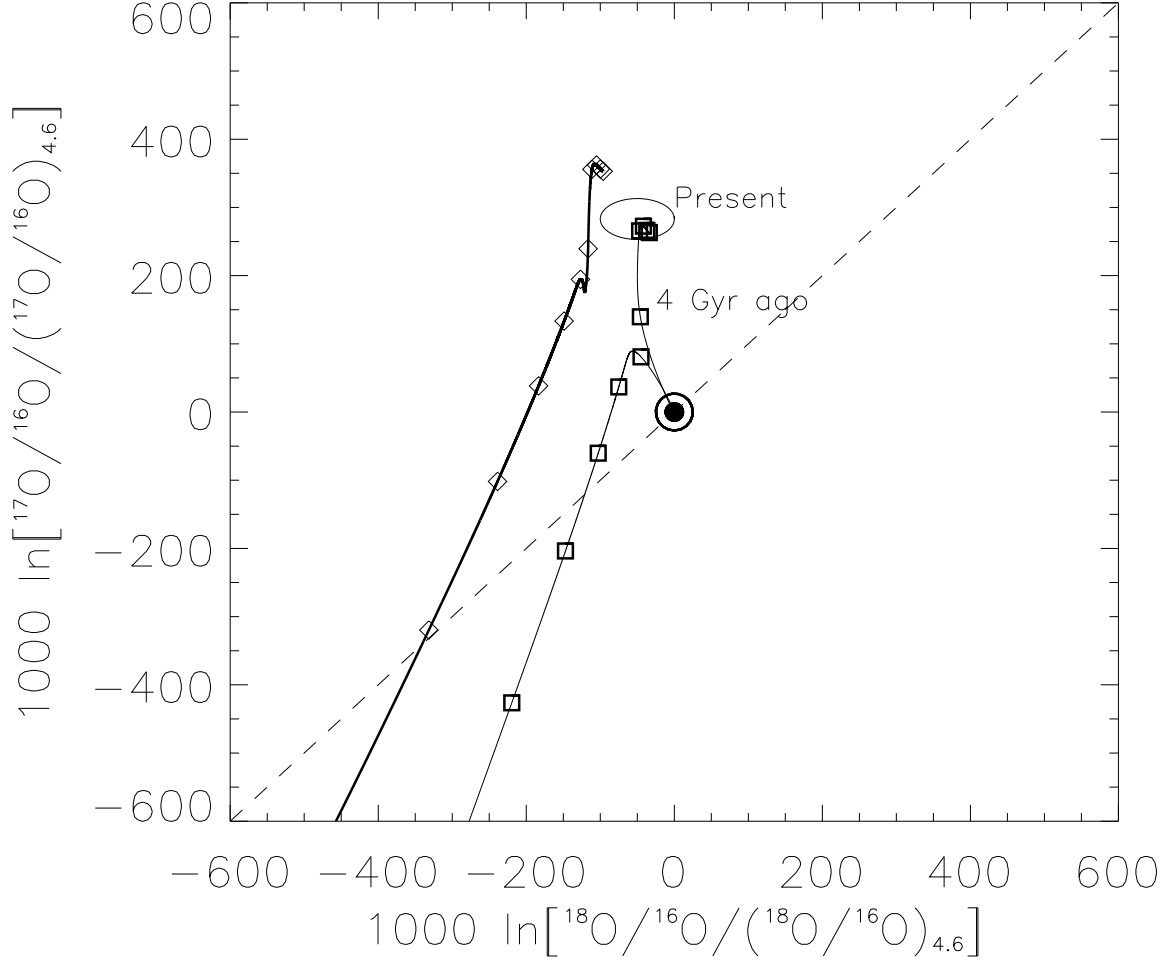
Fig. 2.— Same as Figure 1, except with a period of elevated (2×) star formation coinciding with the birth of the Sun. The event is modeled as a gaussian with a standard deviation of 250 Myr. During the event the $^{18}O/^{17}O$ ratio increases as more massive stars eject ^{18}O into the ISM; more slowly-evolving AGB stars add ^{17}O-rich gas later, returning the ISM and star-forming regions to their former paths.
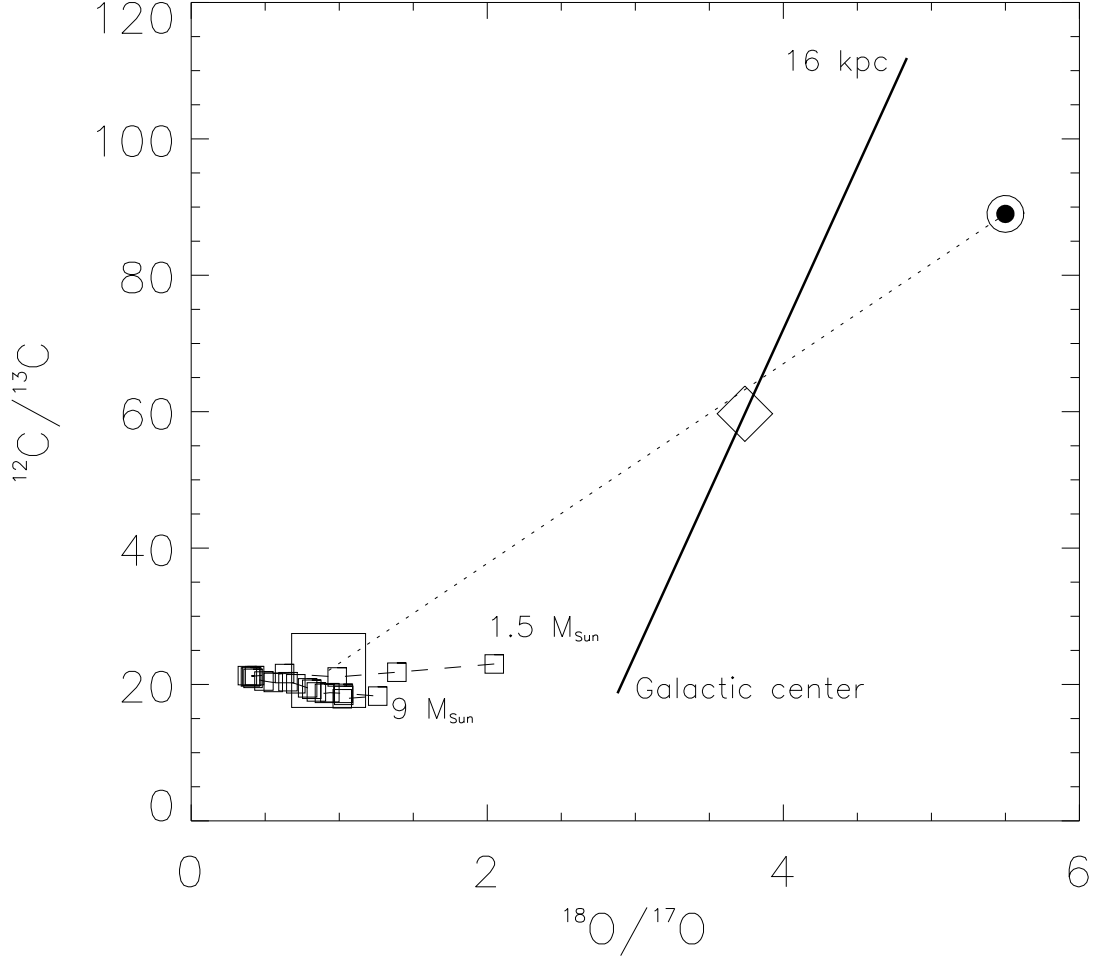
Fig. 3.— $^{12}C/^{13}C$ ratio vs. $^{18}O/^{17}O$ ratio in the Milky Way: The solid line is the Galacto-centric gradient in the ISM based on Milam et al. (2005) and Wouterlout et al. (2008). The circle is the Solar System value, and the composition of 1.5-9 $M_\odot$ AGB star envelopes after second dredge-up (Boothroyd & Sackmann 1999) are small squares. The large square is the IMF-integrated AGB ejecta composition assuming a Salpeter IMF and the ejecta mass functions of Boothroyd & Sackmann (1999). The dashed line is a hypothetical equal-metallicity mixing line between the mean AGB ejecta composition and interstellar gas 4.6 Gyr ago and at a Galactocentric radius of 6.6 kpc, represented by the Solar System (Wielen et al. 1996). The mixing line passes close to the present composition of the ISM at 6.6 kpc (diamond), indicating that it can be produced by addition of AGB ejecta to the ISM at that location 4.6 Gyr ago.